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Towards an integrated forest fire danger assessment system for the European Alps

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ABSTRACT

In recent years the European Alps experienced higher temperatures, more heatwaves, and more severe wildfires. Improving fire danger assessment for these sensitive ecosystems is a core element of future-oriented fire management strategies in the face of climate change. While meteorological systems are common to predict fire danger in many countries, other factors such as vegetation, topography, lightning occurrence and human impact are generally not considered. We introduce an Integrated forest Fire Danger assessment System (IFDS) for the Alpine country Austria that includes i) daily fire weather index data, ii) a countrywide hazard map for fire ignition through human activities, iii) a lightning fire hazard map, iv) a high-resolution fuel type map, and v) a topography-based estimation of the fire hazard. The system was implemented as an online Web-GIS prototype. The objectives of this contribution are to describe the conceptual approach for the IFDS, to understand the predictive power of different data layers in fire danger rating and to identify potential improvements, especially regarding the role of vegetation and human influence. A first validation was done with 2018–2019 forest fire data. Some variants of the IFDS produced better overall prediction accuracy regarding forest fire ignitions compared to common fire weather indices. They typically performed relatively better when considering the number of false alerts as well. However, correlation between larger burned areas and higher index values was low. Conclusions for the implementation of the IFDS in other Alpine countries are discussed and recommendations for necessary and reliable datasets at high resolution are given.

1. Introduction

In recent years, major wildfires in Australia, Brazil, California and Siberia provided evidence that wildfire occurrence and severity are increasing as the climate changes (Abatzoglou and Williams, 2016; Mariana et al., 2018). Several studies and extraordinary fire events, like the simultaneous outbreak of large forest fires in the Italian region of Piemonte in October 2017, demonstrated that wildfires are also an urgent issue in the European Alps and that frequency and severity will likely increase in the future (Matulla et al., 2004; Moser et al., 2010; Müller et al., 2015; Valese et al., 2014; Wastl et al., 2013). The probability and intensity of forest fires are driven by higher temperatures in combination with longer drought periods, the change in forest management and a more intensive recreational use of forests (Aldersley et al., 2011; Dupire et al., 2019; Flannigan et al., 2005; Vacchiano et al., 2018; Zumbrunnen et al., 2012). Especially mountain protection forests on south-facing slopes are at risk. Forest fire impacts can lead to new avalanche-prone slopes, rockfall events, mudslides and soil erosion. In the future, costs of firefighting, restoration of forests and prevention measures may increase significantly. Many parts of the Alpine forests consist of spruce (*Picea abies* (L.) H. Karst.), a species that already suffers from climate change impacts and will become even more affected if temperature and dryness rise as expected (Lexer et al., 2014). Another major issue in fire prone regions is the Wildland-Urban-Interface (WUI), as wildfires affect urban areas more easily as a result of the usual practice of constructing buildings, infrastructure and homes near or in the vegetation zone (Fox et al., 2018; Sarricolea et al., 2020).

Besides the analysis of wildfire data, precaution measures, an adapted forest management, awareness raising and the collection of empirical data on fire behavior, an improved wildfire danger assessment is a key element to prevent severe fire impacts and high suppression costs for fires (De Angelis et al., 2015). In most European Alpine countries national weather services or authorities provide an assessment of fire danger at national level. There are also attempts to

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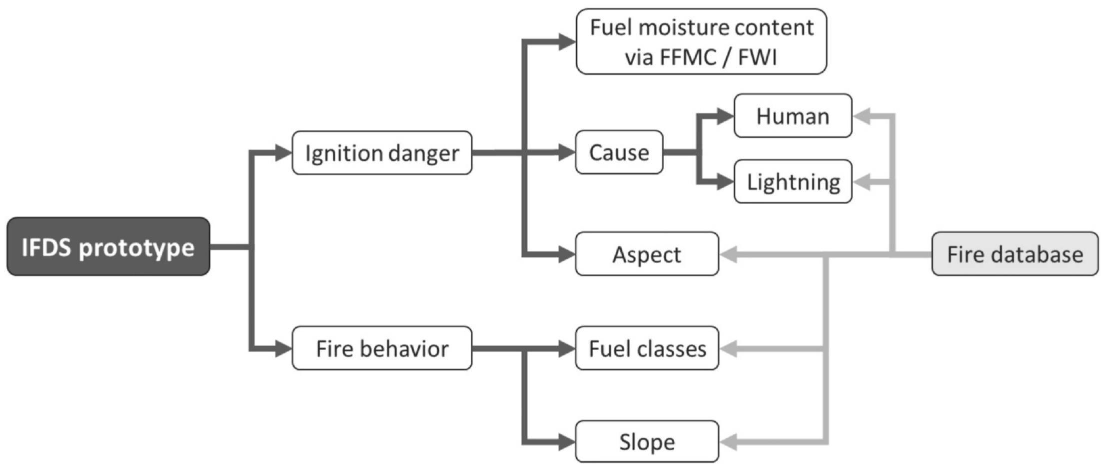

Fig. 1. Schematic illustration of the IFDS prototype and the included data layers.

integrate real-time weather data into GIS platforms to support fire brigades in fighting wildfires (Kalabokidis et al., 2013). Current used fire danger assessment systems in Europe and worldwide have in common that, in most cases, only meteorological data (fire weather indices respectively) are used to predict wildfire danger (De Angelis et al., 2015). There is a need to assess wildfire danger using an integrated and harmonized procedure at European level (Chuvieco et al., 2010; San-Miguel-Ayanz et al., 2018). This procedure has to consider multiple factors, e.g. fire weather, fire causes, vegetation and topography. In the present study, all these factors were considered to estimate fire danger.

For the European Alps, first attempts to include fire causes and potential vulnerabilities into fire danger assessment were done in Switzerland (Conedera et al., 2015). Fire danger modelling in such small-scaled landscapes like the European Alps encounters a number of difficulties. A spatial resolution of 1 km^2 is state of the art of regional weather models but might be insufficient when considering narrow valleys, mountain peaks, and the corresponding effects of temperature, precipitation, wind and solar irradiation on north and south-facing slopes (Carrega, 1995). This leads to an inadequate picture of estimated surface fuel moisture, the crucial part in fire ignition (Schunk et al., 2013; Zhou and Vacik, 2017). Moreover, (fine) fuel moisture is influenced by a number of factors. Besides atmospheric variables and topography, also tree species, vegetation type and structure can alter the fuel moisture (Carrega and Geronimo, 2007; Schunk et al., 2013).

Assessments of wildfire danger often do not consider potential triggers of fires: lightning strikes and human activities. While the direct or indirect anthropogenic influence accounts for nearly all wildfires in southern Europe, about 15% of annual forest fires in the Alps are the result of lightning strikes (Conedera et al., 2006; Müller et al., 2013; Müller and Vacik, 2017). All other wildfires in the Alpine region are most likely anthropogenic caused, often ignited by carelessly discarded cigarettes, pile fires out of control, hot ashes, flying sparks from trains, torn cables of power lines, traditional fires, or arson (Vacik et al., 2011).

Another critical point of currently used fire danger assessment models in the Alpine region is their inappropriate suitability for the winter season and early spring. South-facing slopes are snow-free earlier because of higher temperatures and stronger solar radiation. The fine organic matter from the last year (grass, litter) dries out faster than on north-facing slopes, increasing the probability for an earlier fire ignition in spring (Conedera et al., 2018; Maxwell et al., 2019). This phenomenon cannot be described by current fire danger indices such as the Canadian Fire Weather Index (FWI), as these indices are not intended to be used in the cold season (Van Wagner, 1987).

To overcome the presented issues and to capture all elements of forest fire ignition and fire behavior in a holistic way, the present study introduces an Integrated forest Fire Danger assessment System (IFDS) for the Alpine region. Austria, situated at the eastern border of the Alps, was chosen as case study region. The aim of this study is to i) understand the predictive power of the different datasets used and to ii) discuss potential data insufficiencies. We hypothesize that i) the IFDS has a better fire prediction accuracy than the stand-alone use of meteorological fire weather indices and ii) including the human factor further improves prediction quality.

In our study, we mainly refer to the term *forest fire*, which means an uncontrolled fire independent of size, cause and intensity, affecting forested area. Forest fires are the most relevant type of uncontrolled vegetation fires in the Northern Alps and are used synonym to *wildfires in forested areas*. The term *wildfire* includes all uncontrolled vegetation fires and is used in our study where appropriate. *Aspect* is used as a synonym for *topographical aspect*.

2. Methodological development of the IFDS

The conceptual approach of our IFDS prototype considers the combined use of factors that influence fire ignition danger and fire behavior according to Chuvieco et al. (2010) and San-Miguel-Ayanz et al. (2018). The used datasets and data layers included i) information on forest fire occurrence, retrieved from the Austrian wildfire database, ii) fire weather indices derived from meteorological data, iii) a spatial analysis on the human influence on fire ignition, iv) a lightning fire hazard map, v) an area-wide classification of vegetation to derive a fuel type map, and vi) a high-resolution topography map, where we extracted aspect and slope (Fig. 1). The different combination and weighting of these factors allowed the calculation of several model variants.

2.1. Wildfire database

An Austrian wildfire database was established within the activities of European (ALP FFIRS) and national (AFFRI, FIRIA) funded projects, as no homogenized and nationwide database on vegetation fire occurrence existed (Vacik et al., 2011). The database now contains more than 6500 wildfire incidents, including 5000 forest fires, with an almost complete documentation of 1300 forest fires larger than 0.1 ha since 1993 (Müller et al., 2020). The mean localization error for all recorded forest fires in the Austrian fire database is below 1500 m. Additional information on the recorded fires includes totally burned area, affected tree species and forest type, fire causes, fire behavior, altitude, slope and topographical aspect at ignition point. All fire ignition points are georeferenced in WGS 84. The Austrian forest fire database was used as empirical basis to define the danger classes of the data layers on fire weather, human influence, lightning induced fires, vegetation, aspect and slope. The data layers implemented in our IFDS were generated during different projects and in different years (Appendix A). Therefore, the respective forest fire records used differ in terms of accuracy and time span. For the IFDS validation, forest fire data of 2018 and 2019 were used.

2.2. Meteorological data

Weather conditions influence fire ignition and fire behavior. The Canadian FWI as predictor of both fire ignition and fire behavior is successfully implemented by several European countries, including the European Forest Fire Information System (EFFIS) hosted by the Joint Research Center (JRC). It consists of several sub-indices, which describe the fuel moisture and wind dependent fire behavior. Arpaci et al. (2013) proved that the FWI and its sub-indices performed best regarding the prediction of forest fire occurrence in Austria compared to other fire weather indices and meteorological variables.

We used fuel moisture as the weather-related proxy for ignition danger (Schunk et al., 2013). In Austria, fire ignition is assumed to be more relevant than fire behavior. There are only few forest fires in Austria, about 200 per year, 95% of which burn less than one hectare and 85% even stay below 0.1 ha – a size, where forest fire behavior is not yet of great importance. Even a fire with a burned area of about ten hectares (which occurs on average every three years) is very small on a global scale. According to forest fire documentation, fire behavior in Austria depends more on vegetation and topography than on meteorological conditions (Vacik et al., 2011). Forest structure in Austria and in other Alpine regions is heterogeneous and often interrupted by forest roads, clear-cuts, alpine pastures or skiing slopes. This enables early and direct intervention and can prevent large fires, where fire behavior prediction is crucial for effective and safe firefighting and evacuation measures (Beck et al., 2002).

The Fine Fuel Moisture Code (FFMC), a sub-index of the FWI, shows better prediction results for fire ignitions than the FWI, also in Austria (Arpaci et al., 2013; Dowdy and Mills, 2012). Daily FFMC data are available since 2019. Therefore, we could use the FFMC as a basis for the calculations of the IFDS variants only in 2019. In 2018, fuel moisture in our model was depicted through the FWI.

The FWI and its sub-indices are estimated by the Austrian Central Institute of Meteorology and Geodynamics (Zentralanstalt für Meteorologie und Geodynamik, ZAMG), using the INCA approach (Integrated Nowcasting through Comprehensive Analysis). INCA provides short-term forecasts and analysis of temperature, relative air humidity, rainfall, and other parameters on a spatial resolution of 1×1 km nationwide (ZAMG, 2019). The model requires topographic information for a realistic description of the local weather conditions. However, as the resolution is limited to 1×1 km, effects of aspect or slope inclination cannot be depicted at a fine-scale. Wind is the most crucial factor regarding fire propagation (Chuvieco et al., 2010). Yet, there is no reliable high-resolution wind model for the mountainous region of Austria available that could be used to model fire behavior. Therefore, the factor wind was excluded in the current approach.

In our IFDS prototype, we defined the FWI and FFMC danger class thresholds based on the analysis of Austrian forest fire data from 2012 to 2018, literature review and expert judgements. Because of the poor performance of the Canadian FWI in late autumn, winter and early spring, thresholds for this index were modified using an expert-based approach to gain better prediction accuracy (Table 1). According to international standards, five danger classes were defined from 1 (very low) to 5 (very high). Lower thresholds were given to the lower danger classes and higher thresholds to the two highest danger classes, in order to record few forest fires in danger class 1 and to avoid a large-scale over-warning with high fire danger (Table 1).

Table 1
Canadian FWI, its sub-index FFMC and the corresponding thresholds of the danger classes used for the IFDS prototype.

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
FFMC	< 78	$78 < 87$	$87 < 91$	$91 < 93$	≥ 93
FWI (15.04–15.10)	< 5	$5 < 10$	$10 < 20$	$20 < 40$	≥ 50
FWI (16.10–14.04)	$< 2{,}5$	$2{,}5 < 8$	$8 < 17$	$17 < 36$	≥ 36

2.3. Human impact

Human activities are the most relevant ignition source of wildfires in Europe (Aldersley et al., 2011; Zumbrunnen et al., 2012). In Austria, 85% of all forest fires are anthropogenic caused (Vacik et al., 2011). Arndt et al. (2013) estimated human influence on fire ignition by studying the relationship between touristic activities, infrastructure, forestry and the spatial occurrence of forest fires from 1993 to 2009 using logistic regression. They identified 59 socio-economic variables, which were validated using different models and subsets of forest fire records. In the final model, the variables that significantly contributed to fire ignitions were railroads, forest roads, population density and hiking trail density together with agricultural and forest infrastructure. The authors could explain around 60% of the forest fires causes and prepared a fire hazard map for the whole of Austria at municipal level. This map was used as basis for the human data layer in our model (Appendix A).

2.4. Lightning fires

Lightning strikes are the only relevant natural cause of fire ignition in Europe (Conedera et al., 2006). In Austria, 15% of all forest fires are caused by lightning. During the summer months, the proportion can be up to 50% (Müller et al., 2013). After a validation procedure for lightning strikes that ignited forest fires in Austria from 1993 to 2012 (Müller et al., 2013), spatial lightning fire data was intersected with a high-resolution topographic map and a vegetation map (Albers, 2012; Grima, 2011). The parameters used for danger classification were altitude, slope inclination, aspect and vegetation type. Based on the distribution of lightning fires from 1993 to 2012, a static raster layer with danger classes from 1 to 5 at a spatial resolution of 100×100 m was compiled (Appendix B). The combination for the final lightning fire hazard map was done by equal weights (25% per parameter), as currently no studies on the importance of the different factors are available for Austrian conditions.

2.5. Vegetation

Vegetation type, amount, composition, structure and patchiness influence fire behavior (San-Miguel-Ayanz et al., 2018) and are referred to as fuel characteristics (combustible material). In Austria, there is no such fuel type classification available. In our IFDS model, we used a nationwide vegetation map of Austria as basis for the fuel classification. Input datasets were the Austrian National Forest Inventory (BFW 2002) and the Corinne land cover (CLC) map from 2006 with information about forest type (deciduous, coniferous, mixed stands dominated by deciduous or coniferous) and data on biomass load (low, moderate, high). Albers (2012) and Arpaci et al. (2011) provided a map with a spatial resolution of 100×100 m, where burnable fuels and non-burnable areas (high-mountainous, lakes, sealed surfaces) were displayed. All burnable fuels were classified into five danger classes according to fire occurrence in Austria from 1993 to 2010 and validated by a study in Tyrol (Oettel, 2012) and Carinthia (Grima, 2011). Agricultural land and meadows were defined as danger class 1. Pure deciduous forests, mixed forests dominated by deciduous trees and sparse vegetation (e.g. alpine tree line, scattered high-altitude vegetation not mapped as forest) were classified as danger class 2. Danger classes 3 to 5 were assigned to coniferous forests, where pure coniferous forests with high fuel load were given danger class 5.

2.6. Topography

Topographical effects are not depicted in the FWI and FFMC calculations retrieved from ZAMG, but both aspect and slope are essential parameters for fire ignition danger and fire behavior assessment, respectively. Aspect and slope were derived from high-resolution topographic maps, available online at the open data center for Austria (https://www.data.gv.at). We resampled these data layers from their original spatial resolution of 10 × 10 m to 100 × 100 m, to match them with the rest of data layers in our IFDS.

Because of stronger solar radiation and higher temperatures, south-facing slopes are drier than northern ones. This leads to a lower fine fuel moisture content and therefore a higher ignition probability (Conedera et al., 2018; Maxwell et al., 2019). Fuel moisture also affects fire behavior, however, we assumed that its relevance in the Alpine region is higher for fire ignition danger (cf. Section 2.2). We classified the topographical aspect in five danger classes, based on forest fire data from 1993 to 2017. Most fires were recorded on south-facing slopes (danger class 5), followed by southwestern (4) and southeastern slopes (3). Western, northwestern, northeastern and eastern slopes were categorized as danger class 2. Northern slopes had the lowest share of forest fires; therefore, the danger class was defined as very low (1). We excluded all areas with a slope inclination of < 5° from the evaluation, as effects of solar radiation were assumed to be less relevant when slope inclination falls below this value.

Slope inclination contributes to fire behavior (Chuvieco et al., 2010; San-Miguel-Ayanz et al., 2018). It mainly influences the rate of spread and, thus, the burned area (Csontos and Cseresnyés, 2015). We converted slope inclination into fire danger classes based on Albers (2012) and the evaluation of fire records and burned areas from 1993 to 2017. Slopes with an inclination of 40–49° were assessed as danger class 5, since fire spreads faster on steeper slopes. Areas with an inclination of < 10° and ≥ 50° were categorized as danger class 1, because of the lower propagation danger in flat surfaces (Boboulos and Purvis, 2009) and the lack of continuous forest cover in very steep areas. An overview of the classifications and thresholds of the data layers vegetation, slope and aspect is given in Table 2.

2.7. Combination of factors

We combined the data layers shown in Fig. 1 using different weighting approaches (Table 3). This was done to test the sensitivity of the parameters / combinations in predicting forest fire danger. We based the weighting of the variants on results of previous studies in the Alpine context (Albers, 2012; Arpaci et al., 2013; Grima, 2011; Müller et al., 2013; Müller and Vacik, 2017). For variants 1 to 5, the weighting of the factor lightning was altered according to the season. From May 15th to September 15th, lightning was given high relevance (50%), as lightning strikes may ignite up to 50% of all forest fires in Austria during the summer months (Müller and Vacik, 2017). Since almost no lightning fires are documented for the rest of the year, the weighting of the factor lightning was set to zero, leading to 100% human cause. Variant 6 was seen as a control model with equal weighting for all parameters.

2.8. Technical implementation

The IFDS prototype runs on an Ubuntu server and is based on the Python web framework "Django", which allows an easy management of large amounts of data. The frontend of the Web-GIS application is based on HTML, CSS and JavaScript. JavaScript with its libraries jQuery and Leaflet are used for the client-side functions of the website. The first is a library for the efficient processing of the so-called "document-object model", i.e. the structure of the webpage, while the latter is used to display the map. Currently, the prototype is available on a password-protected server under https://www.waldbrand.at ("forestfire.at") (Fig. 2).

With the exception of the FFMC / FWI values, which are daily updated and delivered to the server, the data layers used for the IFDS prototype are of static nature. All datasets are available at a spatial resolution of 100 × 100 m, leading to matrices of 5731 × 2951 cells to cover all of Austria. We converted the FFMC / FWI calculations from the original 1 × 1 km grid to the 100 × 100 m spatial resolution used in the IFDS prototype. For this purpose, the Python framework "Numpy" is used, which was developed especially for large arrays/matrices. For the provision of data layers and calculated indices, "Mapserver", a free web map tool for converting raw map data into retrievable tiles, was used.

The experimental operation of the IFDS prototype started in spring 2018 and is an ongoing research project. Several improvements have already been implemented on the platform, e.g. a calendar feature, a function to generate new weighting variants, the georeferenced display of documented forest fires, and an analysis tool (Fig. 3).

3. Validation

3.1. Fire events and fire danger

For our analysis, we used 135 forest fires from the year 2018 (annual total 172) and 195 forest fires from 2019 (annual total 235). We did not include other vegetation fires in this study. We compared the number of correct predicted forest fires given by the FFMC, the FWI and all mentioned variants. A correct prediction was defined as a fire occurring in the danger classes 3 (moderate), 4 (high) or 5 (very high). A wrong prediction was defined as a fire occurring in the danger classes 1 (very low) or 2 (low). Since the mean localization error for documented forest fires is several hundred meters, and due to assumed inaccuracies in the data layers used, we decided to compare two approaches: First, we analyzed the 100 × 100 m grid cells where ignition points of forest fires were located. Second, we analyzed the 100 × 100 m grid cells together with the surrounding eight cells, leading to a 300 × 300 m data grid. This procedure was only implemented for the variants, not for the FWI and FFMC data layers with a spatial resolution of 1 × 1 km. The nine-cell approach, the results of which are shown in this paper, led to slightly better prediction results of the variants, likely because it smoothed existing data inaccuracies within single grid cells.

To account for the false alert rate, we counted the number of 100 × 100 m grid cells per danger class and variant on all fire days (days with at least one forest fire). We differentiated between the years 2018 and 2019, as the FWI was the basis for variant calculation in 2018

Table 2
Danger classes, classification and thresholds of the data layers vegetation, slope and aspect implemented in the IFDS prototype.

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Vegetation	Agricultural land meadows	Deciduous / mixed sparse vegetation	Coniferous low fuel load	Coniferous med. Fuel load	Coniferous high fuel load
Slope	< 10° / ≥ 50°	10–19°	20–29°	30–39°	40–49°
Aspect	N	W / NW / NE / E	SE	SW	S

Table 3
Variants of the IFDS and weighting of fire weather indices and parameters according to the used data layers for the summer term 2019. The weighting is divided into Ignition danger (left) and Fire behavior (right). The numbers in bold in the respective left column indicate the weighting for Ignition danger / Fire behavior for the listed variant (row total = 100%). Ignition danger is composed of FFMC, Aspect and Cause (row total = 100%), whereby the cause is divided into Human and Lightning (row total = 100%). Fire behavior consists of Fuel classes and Slope (row total = 100%).

	Ignition danger	FFMC	Aspect	**Cause**	Human	Lightning	Fire behavior	Fuel classes	Slope
Variant 1	**80%**	60c	20%	**20%**	50%	50%	**20%**	75%	25%
Variant 2	**80%**	30%	20%	**50%**	50%	50%	**20%**	75%	25%
Variant 3	**90%**	70%	20%	**10%**	50%	50%	**10%**	75%	25%
Variant 4	**50%**	60%	20%	**20%**	50%	50%	**50%**	75%	25%
Variant 5	**100%**	60%	25%	**15%**	50%	50%	**0%**	0%	0%
Variant 6	**50%**	34%	33%	**33%**	50%	50%	**50%**	50%	50%

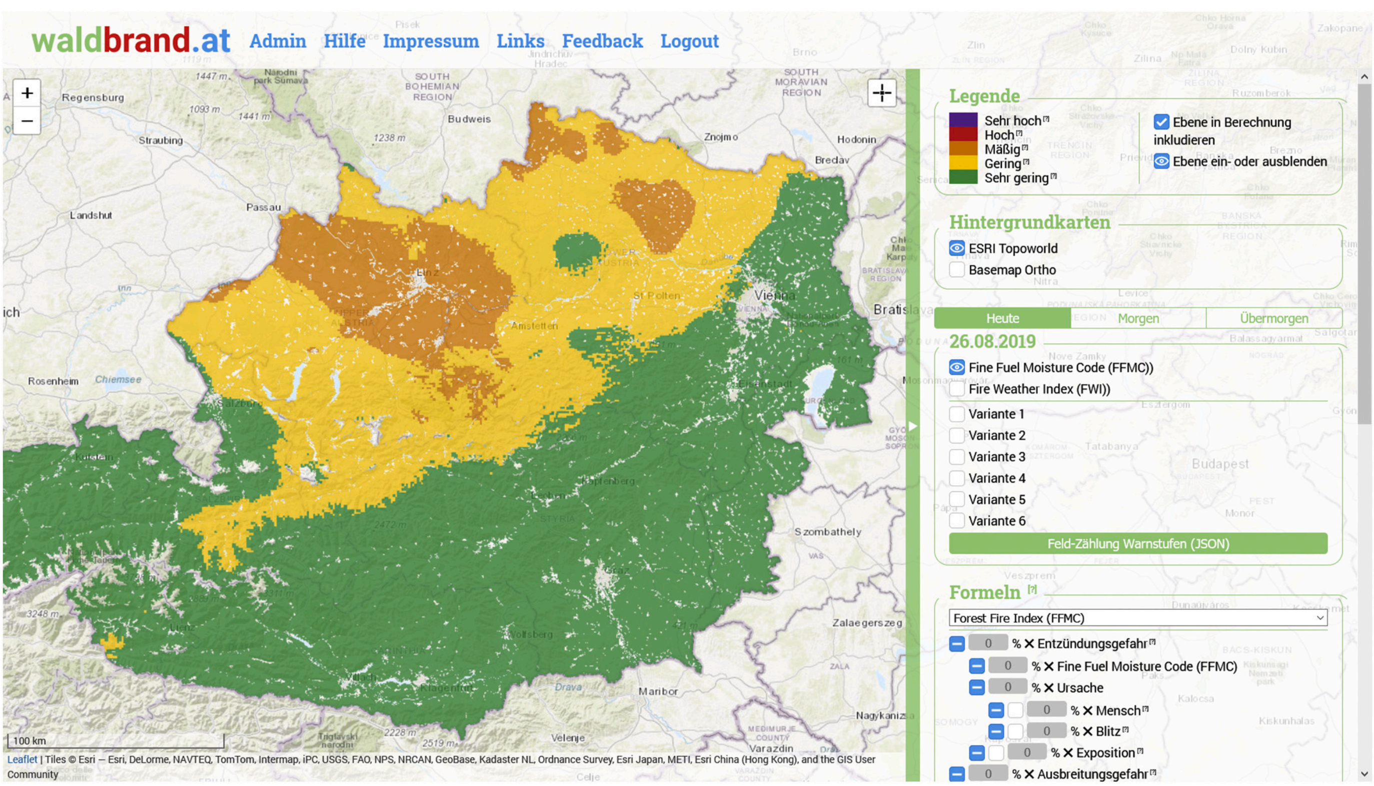

Fig. 2. Screenshot of the Web-GIS application. The colored map represents the FFMC danger classes for August 26, 2019 in the north of Austria. Green colored fields mean a "very low" (1) fire danger, yellow "low" (2) and orange "moderate" (3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the FFMC was the underlying index in 2019. All cells with a danger class of 3 to 5 were evaluated as false alerts. Data grid cells above timberline and in non-burnable areas were excluded from this investigation.

We applied Pearson's chi square tests to test for significant differences in the performance of the FWI, the FFMC and the variants of the IFDS. We applied linear regressions to analyze the relationship between burned area and the classification of forest fire cases into danger classes according to the different variants. For the linear regressions, we only used forest fires with a burned area greater than or equal to 0.1 ha (n = 22 in 2018; n = 26 in 2019), to filter out the numerous small fires.

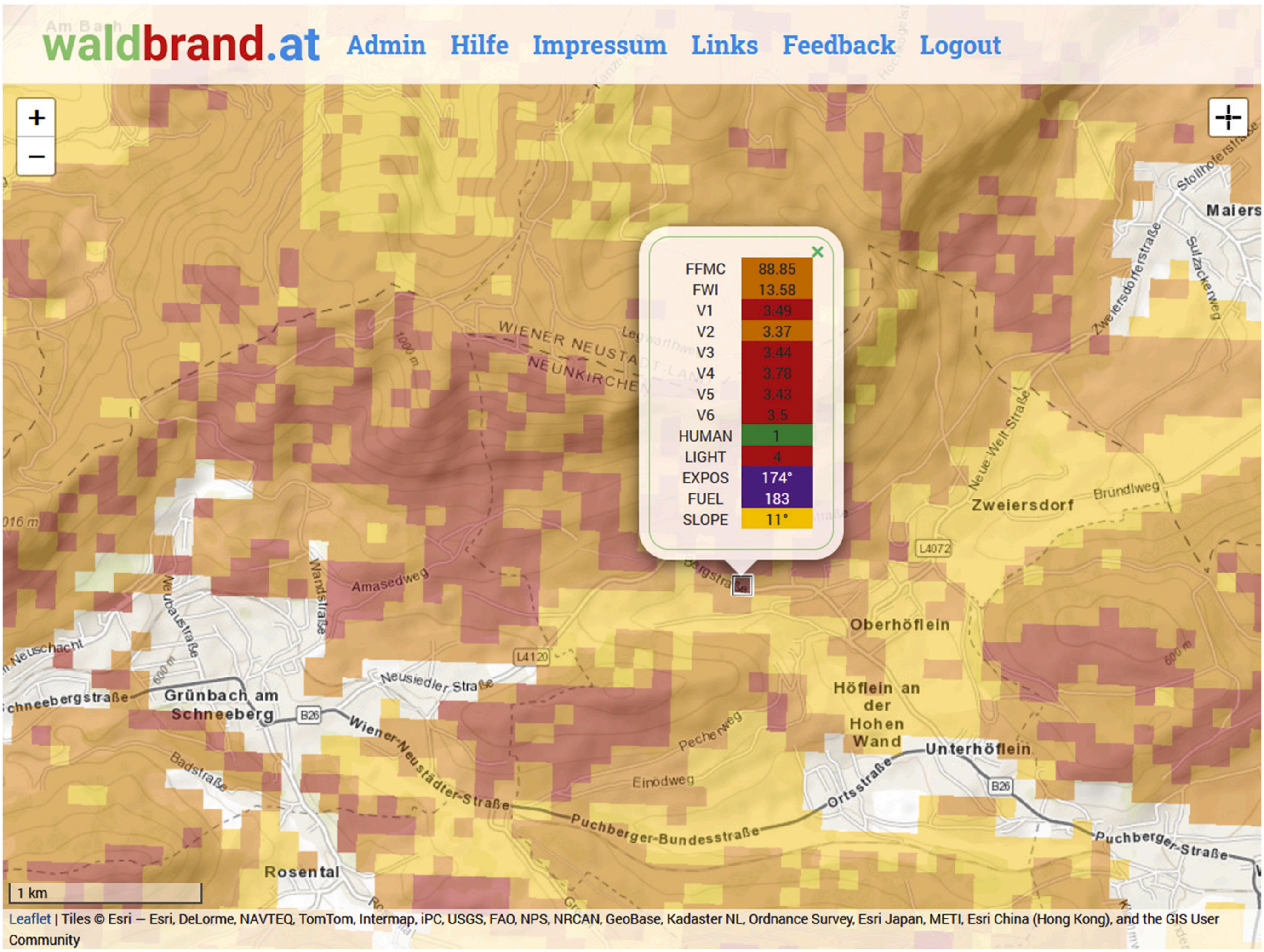

Fig. 3. Screenshot of the Web-GIS prototype for weighting variant 1 on August 19th, 2019. The implemented analysis tool highlights the values of all available data layers for the selected 100 × 100 m grid cell and the selected day (box).

3.2. Findings

We identified clear differences between the performance of the FWI, the FFMC and the IFDS variants. In 2018, the stand-alone FWI had a correct prediction rate of 37% and a false alert rate of 30% (Fig. 4). In other words, by using the FWI, 37% of all forest fires were recorded in grid cells assessed with the danger classes moderate (3), high (4) or very high (5) and 63% were assigned to cells with low (2) or very low (1) danger classes. On the other hand, 30% of all grid cells on fire days were assigned to the danger classes 3–5 without occurring fires.

In 2018, Variant 4 showed the best absolute performance with 50% correct predicted forest fires. This was significantly better ($p < 0.05$) than the FWI, variant 2 and variant 6. Variant 4 also had a lower false alert rate of 16%. Variant 2 performed worst with only 34% correct predictions, but also had a low false alert rate of 16%.

In 2019, the picture was different (Fig. 5). Pearson's chi square results showed that the performance of all variants was significantly better than the FWI ($p < 0.001$) while only variant 4 had a significantly better performance than the FFMC ($p < 0.01$). The stand-alone FWI had the worst correct prediction rate (32%) with 35% false alert rate. The stand-alone FFMC (used for variant calculations in 2019) performed better with 42% correct predicted forest fires and 36% false alert rate. The highest correct prediction rate was again found for variant 4 (58%) with a false alert rate of 28%. Variant 6 showed the second highest correct prediction rate (52%) and also the lowest false alert rate (26%). Variant 2 achieved 51% correctly predicted fires and had a false alert rate of 27%.

No correlations could be found between the burned forest area and the calculated values of the fire weather indices / variants. Higher values of some variants slightly correlated to larger burned areas when applying the nine-cell-approach, however correlation factors were very low (Appendix C).

4. Discussion

4.1. Validation study

With the first version of our IFDS prototype and the preliminary weighting variants, we were able to produce significantly better prediction results than the stand-alone use of the common Canadian fire weather index FWI and its sub-index, the FFMC. Variant 4 performed the best for both years with a possible correct forest fire prediction rate of up to 60%. There were few significant differences between the variants. Variant 4 includes ignition danger and fire behavior with 50% weight each. Fire behavior in our model is primarily driven by the fuel type. The good performance of variant 4 may be due to the fact that most forest fires in Austria ignite in (high-load) coniferous forests. With the current IFDS approach – and especially with variant 4 – it is possible to aim either at a low false alert rate of under 20% by using FWI as basis for calculation, or at a high correct detection rate of about 60% by

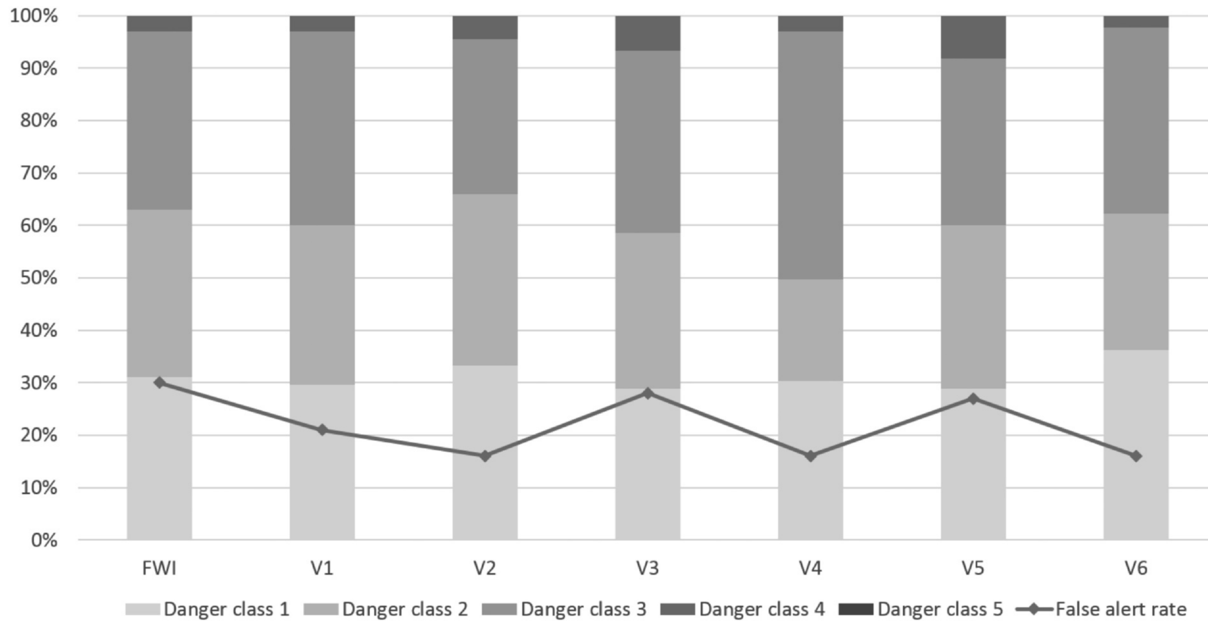

Fig. 4. Validation of the IFDS for 2018. The bars depict the distribution of occurred forest fires per variant and danger class (n = 135). The false alert rate, respectively the percentage of grid cells on fire days in the danger classes 3–5, is indicated by the line.

selecting the FFMC. Both approaches have their justification and can be chosen by fire management experts according to their objectives.

Although we filtered out smaller fires, no correlation could be found between larger burned areas and higher indices/variant values. Besides stochastic effects leading to this picture, Austria has a highly efficient network of voluntary fire brigades. With more than 300.000 active members (of 9 million inhabitants in Austria), about 30 helicopters available and fire brigades in almost every village, the average initial attack time for reported forest fires is under 20 min even in remote areas. This fact helps to keep fires small, even under high fire danger situations. In addition, the years 2018 and 2019 lacked longer periods of drought in combination with windy conditions in the Austrian mountain regions. Therefore, the likelihood of severe and/or large fires was low, resulting in mostly small fires. It is likely that fire prone conditions will increase in the coming years, with more days with high fire danger, also in mountainous regions. A recent study from Portugal pointed out that larger burned areas can be linked to higher values of the Canadian FWI and that resistance to fire spread decreases under more complex topography (Fernandes, 2019).

4.2. Human factor and vegetation

As shown in the current analysis, variant 2 – which includes the highest weight of the human factor – had the worst prediction accuracy in 2018. In 2019, variant 2 led to a higher prediction rate than other variants. However, the differences between the variants were not

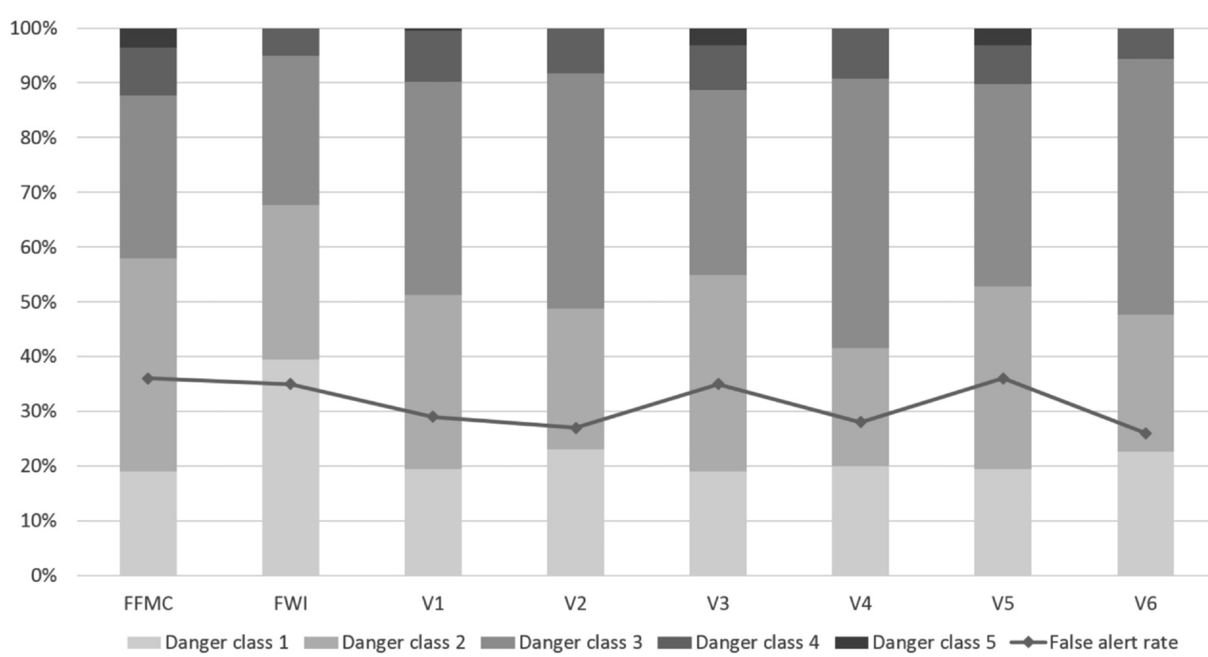

Fig. 5. Validation of the IFDS for 2019. The bars depict the distribution of occurred forest fires per variant and danger class (n = 195). The false alert rate, respectively the percentage of grid cells on fire days in the danger classes 3–5, is indicated by the line.

significant, and variant 4, which only partly considers the human influence, had the best overall prediction accuracy of all variants. These findings are contrary to the fact that 85% of forest fires in Austria are directly or indirectly ignited by humans (Vacik et al., 2011). We assume that the assessment of human impact at the community level with a logistic regression model had some limitations (Arndt et al., 2013). This approach seems to be inadequate because of the highly stochastic nature of fire ignitions. A revised approach to estimate the anthropogenic influence at a spatial resolution of 100 × 100 m would be required.

Although weighting variants including the vegetation layer (e.g. variant 4) showed a good prediction performance, there are some data insufficiencies. Vegetation at the tree line, e.g. mountain pine forests (*Pinus mugo* Turra), are poorly captured by our data layer but are highly flammable, as a recent study in North Tyrol has shown (Sass, 2019). Small forested (or deforested) areas are sometimes not associated with the correct type of vegetation. A differentiation by tree species is necessary, as studies have shown that some species are more fire prone than others (Müller and Vacik, 2017). Efforts are being made to improve the classification of fuel types for Austria with the help of high-resolution Sentinel data and aerial laser scan images (Hollaus et al., 2007).

4.3. FFMC

We preferred to use the FFMC instead of the FWI as a basis for the variant calculation, because we concentrated on fire ignition and the FFMC showed better prediction results for forest fires in Austria. However, the calculation of the FFMC is calibrated for Canadian conditions. At the moment, there is no adaption to Austrian forests. A recent study at the University of Natural Resources and Life Sciences Vienna aims to determine fine fuel moisture content of different forest ecosystems and tries to compare the results with the interpolated FFMC data from the INCA approach (Zhou and Vacik, 2017). This analysis can help to improve the predictive power of the FFMC. A study from Switzerland demonstrated how the use of only meteorological variables produced similar or better results than the Canadian FWI (De Angelis et al., 2015). However, these results do not seem to be transferable to Austrian conditions (Arpaci et al., 2013). The German Weather Service (DWD) is currently working on a new grassland fire index. Such an index may be particularly useful in the winter half-year for mountain regions such as the Alps, as it allows a reasonable estimation of fine fuel moisture beyond the scope of the FFMC and FWI (Müller et al., 2020). An improvement of the prediction accuracy of winter and spring fires may also be achieved by including a high-resolution data layer of the actual snow cover. First attempts of such an approach are currently tested in France and Germany (Müller et al., 2020).

Our model is designed to assess forest fire danger and thus predict uncontrolled fires in forested area. However, with some adjustments, it can also be suitable for predicting wildfires in general, e.g. by including a grassland fire index. Currently, the IFDS is not meant to be used for prescribed burning purposes, as this fire management technique is prohibited in Austria.

5. Conclusions

The IFDS is a new and innovative approach to improve forest fire danger assessment in mountainous and heterogeneous landscapes. The overall performance is strongly driven by the included data layers and the accuracy of the high-resolution data. First results indicated that the IFDS performs better than the use of fire weather indices alone. For the current study, we mainly followed an expert-based approach and did not use machine-learning models, as the spatial data still has some insufficiencies. We were able to describe the relationship between the factors that influence fire ignition and fire behavior, and to learn under which conditions the most accurate results can be achieved. A fire danger assessment approach supported by experts was also used in other studies (Jung et al., 2013; Thompson et al., 2013). As soon as the data quality is improved, the IFDS will be updated with new parameters. Besides scientific and technical optimization, the involvement of stakeholders (e.g. fire brigades, forest authorities, national warning centers) in the development of the system is an essential task for outreach, dissemination and operationalization of the system. In this context, we will ask a selected group of experts for feedback on the performance, usability and reliability of the system in spring 2020. A future use of the IFDS could also be the integration into a decision support system, similar to the approach of Kalabokidis et al. (2013).

Some experts believe that it is almost impossible for regions with a low intensity fire regime like the Northern Alps to design an IFDS (Müller et al., 2020). Together with other experts (Barriopedro et al., 2011; Seidl et al., 2014; Valese et al., 2014; Wastl et al., 2013; Zumbrunnen et al., 2012), we take the view that climate change combined with changes in forest management and increasing recreational activities will alter the current fire regime towards a more fire prone one with a higher number of ignitions and more extreme forest fires, also in the Northern Alps. For this reason, it is important to move towards an integrated fire danger assessment system with a high data reliability and a high spatial resolution, to reflect the small-scale structure of the European Alps.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A

Data layers, project title, year of creation and timespan of used forest fire data implemented in the current version of the IFDS.

Data layer	Project	Year	Forest fire data
Human	Austrian Forest Fire Research Initiative (AFFRI) – Master thesis	2012	1993–2009

Lightning	AFFRI / Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change (FIRIA) – Master thesis	2013	1993–2012
Vegetation	AFFRI / FIRIA / Alpine Forest Fire Warning System (ALP FFIRS)	2013	1993–2010
Aspect	AFFRI 2	2018	1993–2017
Slope	AFFRI 2	2018	1993–2017

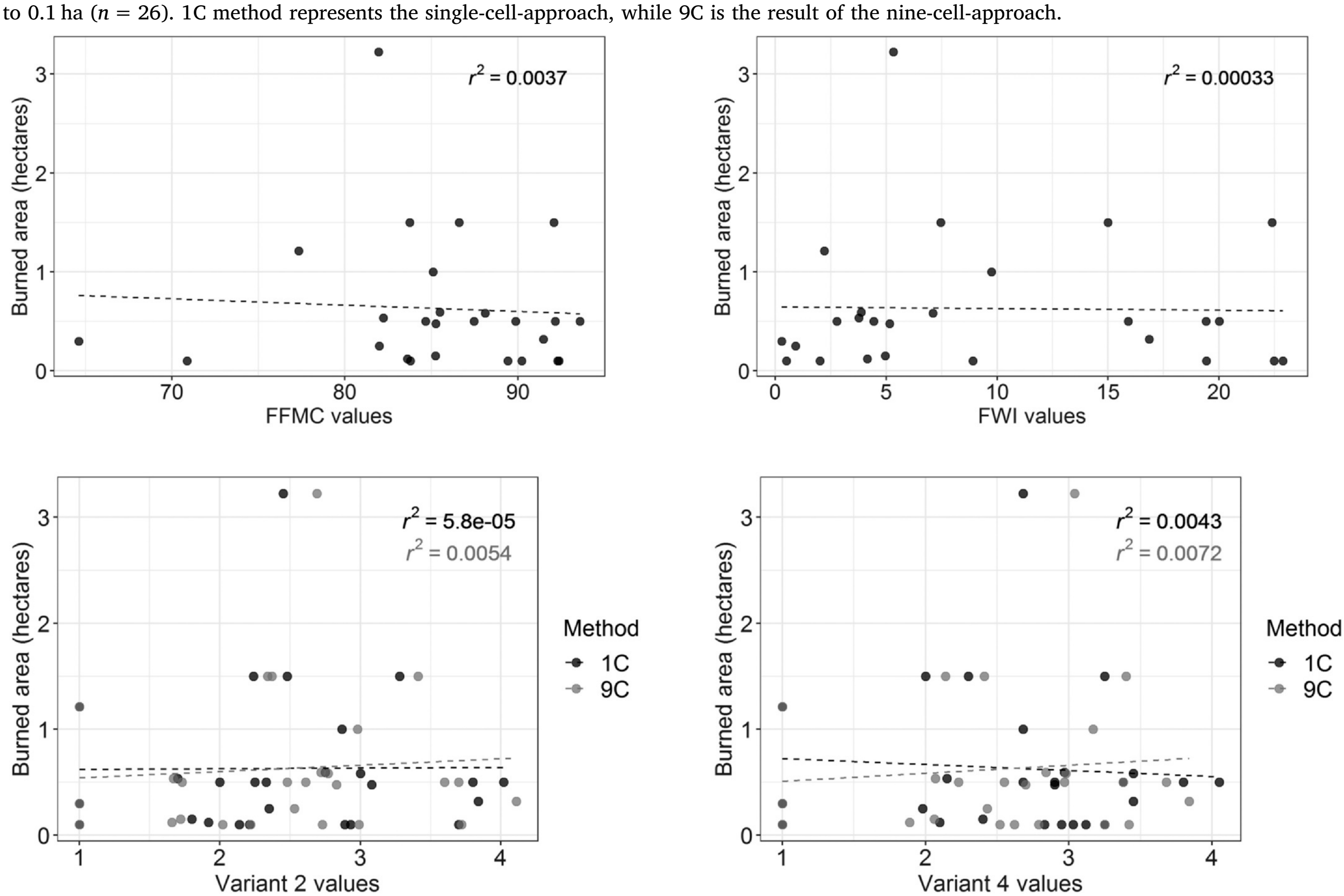
Appendix B

Danger classes, classification and thresholds of the variables used for the lightning fire hazard map implemented in the IFDS prototype.

	Very low (1)	Low (2)	Moderate (3)	High (4)	Very high (5)
Elevation	< 500 m > 2200 m	1800 m – 2200 m	500 m – 800 m	1500 m – 1800 m	800 m – 1500 m
Slope	> 40°	< 10°	30–40°	10–20°	20–30°
Aspect	W / NW / N	E / SW	NE	SE	S
Vegetation type	Deciduous Sparse veg.	Mixed forests	Mountain pine	Coniferous low fuel load	Coniferous high fuel load

Appendix C

Correlation between burned areas of single fires and values of FFMC, FWI and two selected variants in 2019. Shown are only fires greater or equal to 0.1 ha (n = 26). 1C method represents the single-cell-approach, while 9C is the result of the nine-cell-approach.



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